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RESEARCH MEMORANDUM

PRESSURE PULSATIONS ON RIGID AIRFOILS AT TRANSONIC SPEEDS

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON
December 6, 1951

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SUMMARY

The effects of changes in Mach number, thickness ratio, and angle of attack on the amplitude of the pressure pulsations on several airfoils have been obtained at transonic speeds, and the corresponding flows past the airfoils were recorded by high-speed schlieren motion pictures. NACA 65A-series symmetrical airfoils ranging in thickness from 4 to 12 percent chord were investigated at Mach numbers from 0.6 to approximately 1.0 at angles of attack from 0° to 8°. The tests were made in the Langley 4- by 19-inch tunnel operating with a choked diffuser.

A primary conclusion drawn from the present investigation is that reduction in airfoil thickness is accompanied by marked reductions in the magnitude of the aerodynamic-pressure pulsations which are believed to contribute to airplane buffeting at high speeds. This general conclusion, derived from a two-dimensional unsteady flow investigation, is in qualitative agreement with the limited results currently available from flight buffeting investigations.

INTRODUCTION

Flight buffeting investigations on conventional airplanes with unswept wings (reference 1) indicate that, at low speeds, flow separation and buffeting occur as the maximum-lift coefficient is approached but, at speeds near that corresponding to the force-break Mach number, the lift coefficient at which buffeting starts decreases to low values. A recent study, comparison, and correlation of available data pertaining to buffeting are given in reference 2. Buffeting occurring at low-lift coefficients at transonic speeds has been assumed to result from compression-shock effects on the wing. Since a study of shock effects, particularly in regard to steadiness of flow, could be readily investigated in two-dimensional flow, a preliminary investigation of the flow fluctuations on rigid airfoils was conducted in the Langley 4- by 19-inch tunnel. The purpose of this investigation is to present data to assist in an understanding of the fundamental nature of such fluctuating flows, to determine the effect of airfoil thickness on flow fluctuations, and, if possible, to relate the flow pulsations to airplane buffeting. In order to accomplish this purpose, time histories of instantaneous pressure pulsations acting at eight chordwise stations on the upper surfaces of four airfoils were obtained, and the corresponding flows past the airfoils were recorded by high-speed schlieren motion pictures. The data were obtained on NACA 65A-series symmetrical airfoils ranging in thicknesses from 4 to 12 percent chord, at Mach numbers from 0.6 to approximately 1.0, and at angles of attack from 0° to 8°. The Reynolds number of the flow based on the model chord ranged from 1.2 to 1.7×10^6.

APPARATUS, MODELS, AND TESTS

Tests were made in the Langley 4- by 19-inch semiopen tunnel. The tunnel speed was held constant for each test point by a variable throat located in the diffuser downstream from the test section. With the tunnel empty and with the variable throat in use, pressure pulsations of 6 percent of the stream dynamic pressure were observed on the side walls at the position of the model for Mach numbers from 0.7 to near 0.90. At Mach number 1.0, the pulsations in the flow are essentially zero. The frequency of the tunnel pulsation was around 250 cycles per second. Since the 4-inch-chord NACA 65_1A012 airfoil had pressure-pulsation frequencies near this value, it was necessary to determine the effect of the tunnel pulsations on the pulsating pressures on the airfoils. Tests on several 12-percent-thick models of 1.75-, 2.5-, and 4-inch chords indicated that the product of the frequency in cycles per second and chord in inches was approximately a constant (1000) for test Reynolds numbers from 0.7 to 1.7×10^6. It was concluded from these tests that the low-amplitude pressure pulsation in the tunnel of approximately 250 cycles per second had no significant effect on the results presented herein.

A 9-inch-diameter flow field surrounding the models was photographed by a high-speed motion-picture camera utilizing the schlieren method of flow photography. The camera, capable of film speeds from 500 to 5,000 frames per second, recorded a detailed photographic history of the oscillation of the shock waves and flow separation.

Time histories of the instantaneous pressure pulsations acting at eight chordwise stations on the surface of the airfoils were obtained at several constant Mach numbers by miniature electrical induction pressure cells. The pressure orifices were located at 6.25-, 12.5-, 25-, 37.5-, 50-, 62.5-, 75-, and 87.5-percent-chord stations. The pressure cells, mounted on the end plate along the model chord line (fig. 1), were connected to the pressure orifices in the models by short ducts drilled into the end of the models. The calibration factor differed for each cell because small differences existed in the sensitivity of the cells.

A laboratory setup simulating the instrumentation for the models was used in determining the accuracy of the test installation (fig. 2). Double-amplitude pressure pulsations of 21 inches of water were imposed on the orifice in the laboratory test setup at frequencies ranging from 40 to 3000 cycles per second. The indicated pressure response for the cells, ducting, and recording system was accurate to within ±4 percent of a constant value of 1.08 for frequencies of 100 to 400 cycles per second.

The models investigated were NACA 65A-series symmetrical airfoils of 4-inch chord and span, having thicknesses of 4-, 6-, 9-, and 12-percent chord. The airfoil ordinates are presented in table I. The data were obtained at Mach numbers from 0.6 to approximately 1.0 and at angles of attack from 0° to 8°. The corresponding Reynolds numbers were from 1.2 to 1.7×10^6.

RESULTS AND DISCUSSION

Interpretation of Data

Typical portions of the records of pulsations in pressure with time are shown in figure 3 for the NACA 65_1A012 airfoil. For this profile at 0° angle of attack and at a Mach number of 0.87 (fig. 3(a)), there appear to be bursts of roughly fixed-frequency, fixed amplitude oscillations separated by intervals of haphazard fluctuations. The records show high-amplitude pressure pulsations occurring at infrequent intervals, as well as infrequent low-amplitude pressure variations of similar occurrence. These isolated or infrequent pulsations are not considered important as regards buffeting.

For the fixed-frequency type of oscillation, it was found from observations on several 12-percent-thick models of different chords that the product of the frequency and chord was approximately a constant for the test Reynolds number range from 0.7 to 1.7×10^6. Similar unpublished results were obtained at the Ames Aeronautical Laboratory for Reynolds numbers from approximately 3 to 5×10^6. This periodic type of oscillation is considered a characteristic of thick airfoils (reference 3).

It is believed that the amplitude Δp occurring in the fixed-frequency portions of the record is most representative of the force fluctuations which cause buffeting on the airfoil. The pressure pulsation Δp measured from a crest to an adjacent trough of a pressure pulse is the double-amplitude variation of the pressure above and below the average level of pressure existing at the airfoil orifice. These records do not give an indication of the average pressure on the airfoil, since each gage was referenced to a steady pressure near the average pressure existing locally on the airfoil surface.

The airfoil at the higher angles of attack experiences a random-type pulsation. A portion of a record for the NACA 65_1A012 airfoil at an angle of attack of 8° and a Mach number of 0.80 is shown in figure 3(b). The record is characterized by haphazard pressure pulsations of irregular amplitude. The traces for each of the several orifices generally bear a marked resemblance to one another and are approximately in phase. There are pressure pulsations, usually of intermediate amplitude, that appear to predominate. The predominant amplitudes that recur frequently throughout the individual traces are considered the typical amplitudes for this type of record.

The amplitude of the pulsating pressures Δp is expressed in terms of the stream dynamic pressure as $\frac{\Delta p}{q}$. The variation of $\frac{\Delta p}{q}$ along the airfoil chord obtained from figure 3(b) is shown in figure 4 as the typical pressure pulsation along the upper surface. Typical values of the pressure pulsation on the lower surface also have been obtained and are shown. The amplitude of the pressure pulsations for the lower surface is of relatively small magnitude. Thus, the principal contribution to the unsteady flow is made by the upper surface at moderate and high angles of attack. In the analysis that follows, only the upper-surface pressure fluctuations are considered.

The high-amplitude, high-frequency pressure pulsations measured on the upper surface of thick airfoils indicated the probability of a rapidly oscillating flow in the speed range in which the airfoil experienced the pressure pulsations. In order to substantiate the existence of high-frequency oscillations of the shock waves and the point of flow separation on the airfoil in this speed range, high-speed schlieren motion pictures of the flow past the airfoils were obtained. A representative strip of the movie film (fig. 5(a)), consisting of several successive frames photographed at the rate of 5,000 frames per second, illustrates the very rapid flow changes that occur about the NACA 65_1A012 airfoil at an angle of attack of 0° and a Mach number of 0.90. This sequence illustrates the periodic out-of-phase oscillation of the shock waves on the upper and lower surfaces of the airfoil which is a characteristic of the thick airfoils at low angles of attack. Figure 5(b) shows a representative strip of movie film of the flow about the NACA 65_1A012 airfoil at an angle of attack of 6.4° and a Mach number of 0.87. The violent flow fluctuations on the upper surface of the airfoil produce large pressure pulsations.

Schlieren photographs were obtained to illustrate the flow changes that occur on the NACA 65_1A012 airfoil for conditions at which high-pressure pulsations were measured on the airfoil surface. Figure 6(a) shows two instantaneous schlieren photographs of the flow about the airfoil obtained at a constant Mach number of 0.90 and an angle of attack of 0°, and the variation in the pressure pulsations occurring along the upper surface of the airfoil for the same conditions. Similar data are shown in figure 6(b) for the airfoil at an angle of attack of 6.4° and a Mach number of 0.85. Correlation of the schlieren photographs with the pressure measurements indicated that large shock-wave and separation-point oscillations occurred along the airfoil chord and produced the observed pressure pulsations on the airfoil surface. The peak pulsation occurred in the separated-flow region between the mean point of flow separation and the base of the oscillating shock wave.

Pressure Pulsation Measurements

Typical pressure pulsations along the upper surface of the airfoils, as affected by thickness, angle of attack, and Mach number, are shown in figure 7. The 12-percent-thick airfoil at 0° angle of attack first encounters a moderate pulsation at a Mach number of 0.7. As the Mach number is increased, the pulsation increases in amplitude. At a Mach number of 0.87 the peak has moved rearward and the pressure pulsations have increased in amplitude to 22 percent of the stream dynamic pressure. Correlation of schlieren motion pictures with the pressure measurements indicated that the most violent shock oscillation along the chord occurred near this Mach number. Further increase in Mach number causes rapid reduction in the value of $\frac{\Delta p}{q}$. At a Mach number of 1.0, with the shocks at the trailing edge, the pressure pulsations are essentially zero.

As the airfoil thickness is reduced from 12 to 4 percent chord, the pressure pulsations decrease in amplitude. The pressure pulsations on the 4-percent-thick airfoil at 0° angle of attack are relatively small.

With increase in angle of attack from 0° to 8°, there is a general rise in the amplitude of the pressure pulsations, and a forward chordwise movement of the location of the peak amplitudes for all the airfoils. The pressure pulsations that occur on the thin airfoils at lifting conditions are random in nature and less severe than on the thicker airfoils. At angles of attack above 6°, and for Mach numbers from 0.6 to about 0.8, high pulsations occur on the thin airfoils because they are stalled. Slightly above a Mach number of about 0.8, flow attachment occurs at the leading edge (reference 4), after which the pressure pulsations drop abruptly over the front portion of the airfoil and pulsations of much lower amplitude occur only near the foot of the shock. With further increase in Mach number, the shock and location of peak-pressure pulsations move rearward on the airfoil chord. A comparison of the pressure pulsations for the several airfoils shows that the pulsations are much lower on the thin profiles than on the thick profiles.

Relation of Pressure Pulsations to Buffeting

Reference 5 indicates that buffeting on straight-winged aircraft first occurs at a Mach number approximately 0.06 above the lift-divergence Mach number obtained from two-dimensional data for the airfoil corresponding to that at the maximum-thickness-ratio section of the wing. The 0.06 increase in Mach number for the buffeting boundary as determined from two-dimensional data is due to the alleviating effect of finite-aspect ratio on the typical fighter-type aircraft reported in references 2 and 5. These aircraft were of the conventional high-speed type, having a generally high wing loading and were tested over a limited range of altitudes.

Figure 8 has been prepared in order to relate the observed pressure pulsations to the force-break Mach number which is indicative of buffeting. The figure presents the normal-force-coefficient variation with Mach number for the one airfoil, the NACA 65A009 airfoil, for which normal-force data are available at several angles of attack. To the right of the experimental curve for M_{cr}, shock waves are present in the flow. Curves corresponding to pressure pulsations $\Delta p/q$ of 0.10, 0.14, and 0.20 are shown in the figure. A pressure-pulsation level of $\frac{\Delta p}{q} = 0.14$ from the present investigation defines a curve which closely coincides with the Mach number for the lift divergence for this airfoil at the higher angles of attack. Pressure pulsations greater than 14 percent of the stream dynamic pressure exist within the region above the curve, and buffeting of the airplane operating at these conditions has been reported to occur (reference 5).

Results of this investigation are summarized in figure 9. The curves shown in figure 9 represent conditions of Mach number and angle of attack for which the maximum-pressure pulsation at some point on the airfoil has reached a value $\Delta p/q$ of about 0.14. These approximate boundaries were determined from the plots of figure 7 with the aid of high-speed schlieren motion pictures. At low angle-of-attack and Mach number combinations below the curves, the values of $\frac{\Delta p}{q}$ are less than 0.14. As the speed increases and the region to the right of the curve is penetrated, the value of $\frac{\Delta p}{q}$ first increases with Mach number, and then decreases until a second boundary is reached, beyond which $\frac{\Delta p}{q}$ is again less than 0.14. At an angle of attack of 0° the 12-percent-thick airfoil has a value of $\frac{\Delta p}{q}$ greater than 0.14 at Mach numbers from 0.77 to 0.90. For the 9-percent-thick airfoil the flow boundary is similar, except that there is an angle-of-attack range below about 3° in which the fluctuations are less than 14 percent of the stream dynamic pressure. For the 6-percent-thick airfoil the boundary is similar to the thicker models, except that the angle-of-attack and Mach number ranges for small pressure fluctuations have been extended. The general trend shown by the curves for the 6- and 9-percent-thick airfoils is in agreement with the results on flight buffet boundaries presented in reference 2.

At Mach numbers around 0.62 the thinner sections (6- and 4-percent-thick airfoils) have smaller angle-of-attack ranges for low-amplitude pressure pulsations because as a general rule these sections are stalled at angles of attack above 6°. The irregularity in the curve for the 4-percent-thick airfoil near a Mach number of 0.70 is attributed to unsteadiness accompanying the flow attachment at the leading edge of this airfoil. This result was confirmed in the motion-picture flow studies. A line indicating the conditions for the leading-edge flow attachment for the 4-percent-thick airfoil is included in figure 9. This airfoil has a boundary for flow fluctuations of $\frac{\Delta p}{q}$ of 0.14 that parallels the line for flow attachment for this airfoil at a slightly higher Mach number. The agreement of these curves would indicate that most of the unsteady flow associated with shock on the 4-percent-thick airfoil at the higher Mach numbers is caused by the instability of flow attachment at the leading edge of the airfoil. For all Mach numbers above 0.8 the 4-percent-thick airfoil shows relatively steady flow, and no serious force fluctuations would be expected to occur on this airfoil at transonic speeds above a Mach number of 0.8 for angles of attack up to at least 8°, the limit of these tests.

CONCLUDING REMARKS

The amplitude of pressure pulsations associated with shock oscillations on airfoils of 4- to 12-percent-chord thickness has been determined at Mach numbers between 0.6 and 1.0 and angles of attack from 0° to 8°. The peak-pressure pulsations on the airfoils occurred in the region along the chord between the separation point and the main leg of the shock. A periodic-type oscillation was observed only on the thickest airfoil (NACA 65_1A012) near zero lift and over a limited Mach number range. For all other test conditions the oscillations appeared to be random in character.

At a constant angle of attack the peak-pressure pulsations increased in amplitude and moved downstream on the airfoils with increasing Mach number as the shocks moved downstream. Maximum values of the pressure pulsations were reached in the speed range between lift break and lift recovery. Further increase in Mach number produced a decrease in the pressure pulsations. At constant Mach number the amplitude of the pressure pulsations generally increased and the location of the peak-pressure pulsation moved forward with the shock as the angle of attack was increased.

Stalled flow on the thinner airfoils produced high pressure pulsations which were greatly reduced when flow attachment at the leading edge occurred abruptly as the Mach number was increased. At Mach numbers above the attachment Mach number the magnitude of the pulsations decreased markedly as the thickness ratio was decreased. If it is assumed that the amplitude of these two-dimensional pulsations is indicative of the intensity of aircraft buffeting, then large reductions in intensity of buffeting should be obtainable through reduction in wing thickness ratio. The limited flight buffeting data currently available provide qualitative confirmation of this beneficial effect of thickness ratio reduction.

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2. Purser, Paul E., and Wyss, John A.: Review of Some Recent Data on Buffet Boundaries. NACA RM L51E02a, 1951.

3. Daley, Bernard N., and Humphreys, Milton D.: Effects of Compressibility on the Flow Past Thick Airfoil Sections. NACA TN 1657, 1948.

4. Lindsey, W. F.; Daley, Bernard N., and Humphreys, Milton D.: The Flow and Force Characteristics of Supersonic Airfoils at High Subsonic Speeds. NACA TN 1211, 1947.

5. Gadeberg, Burnett L., and Ziff, Howard L.: Flight-Determined Buffet Boundaries of Ten Airplanes and Comparisons with Five Buffeting Criteria. NACA RM A50I27, 1951.

TABLE I.- BASIC SECTION ORDINATES FOR

SYMMETRICAL 65A-SERIES AIRFOILS

[Stations and ordinates are in percent of wing chord]

Station	Ordinate			
	NACA 65A004 airfoil	NACA 65A006 airfoil	NACA 65A009 airfoil	NACA 65_1A012 airfoil
0	0	0	0	0
.5	.11	.464	.690	.913
.75	.378	.563	.837	1.106
1.25	.481	.718	1.068	1.414
2.50	.656	.981	1.463	1.942
5.00	.877	1.313	1.965	2.614
7.50	1.062	1.591	2.385	3.176
10	1.216	1.824	2.736	3.647
15	1.463	2.194	3.292	4.392
20	1.649	2.474	3.714	4.956
25	1.790	2.687	4.034	5.383
30	1.894	2.842	4.266	5.693
35	1.962	2.945	4.420	5.897
40	1.996	2.996	4.495	5.995
45	1.996	2.992	4.486	5.977
50	1.952	2.925	4.379	5.828
55	1.867	2.793	4.174	5.544
60	1.742	2.602	3.881	5.143
65	1.584	2.364	3.519	4.654
70	1.400	2.087	3.099	4.091
75	1.193	1.775	2.631	3.467
80	.966	1.437	2.127	2.798
85	.728	1.083	1.602	2.106
90	.490	.727	1.075	1.413
95	.249	.370	.547	.719
100	.009	.013	.020	.025
L.E. radius:	0.118	0.229	0.516	0.922

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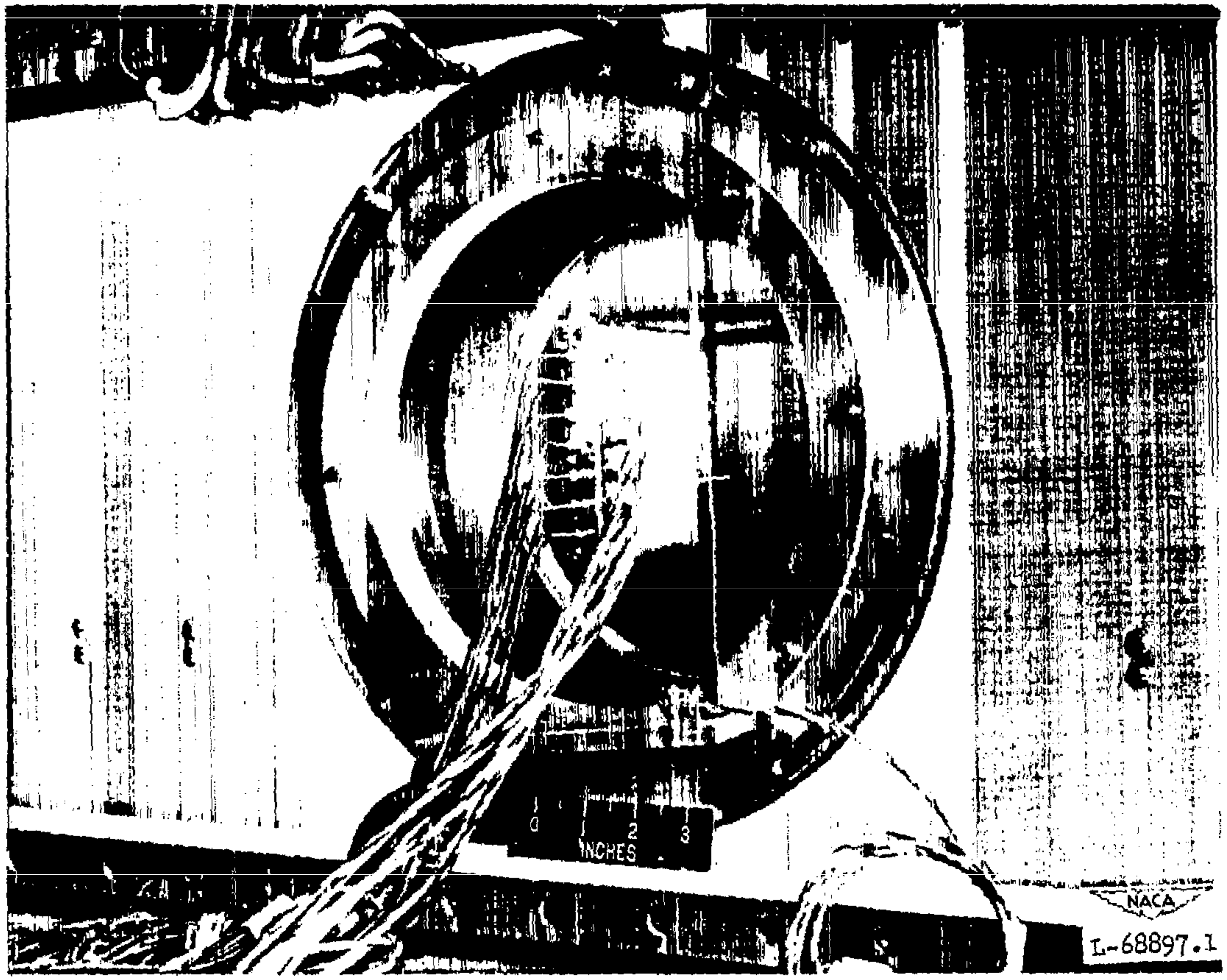

Figure 1.- Model installation in the Langley 4- by 19-inch semiopen tunnel.

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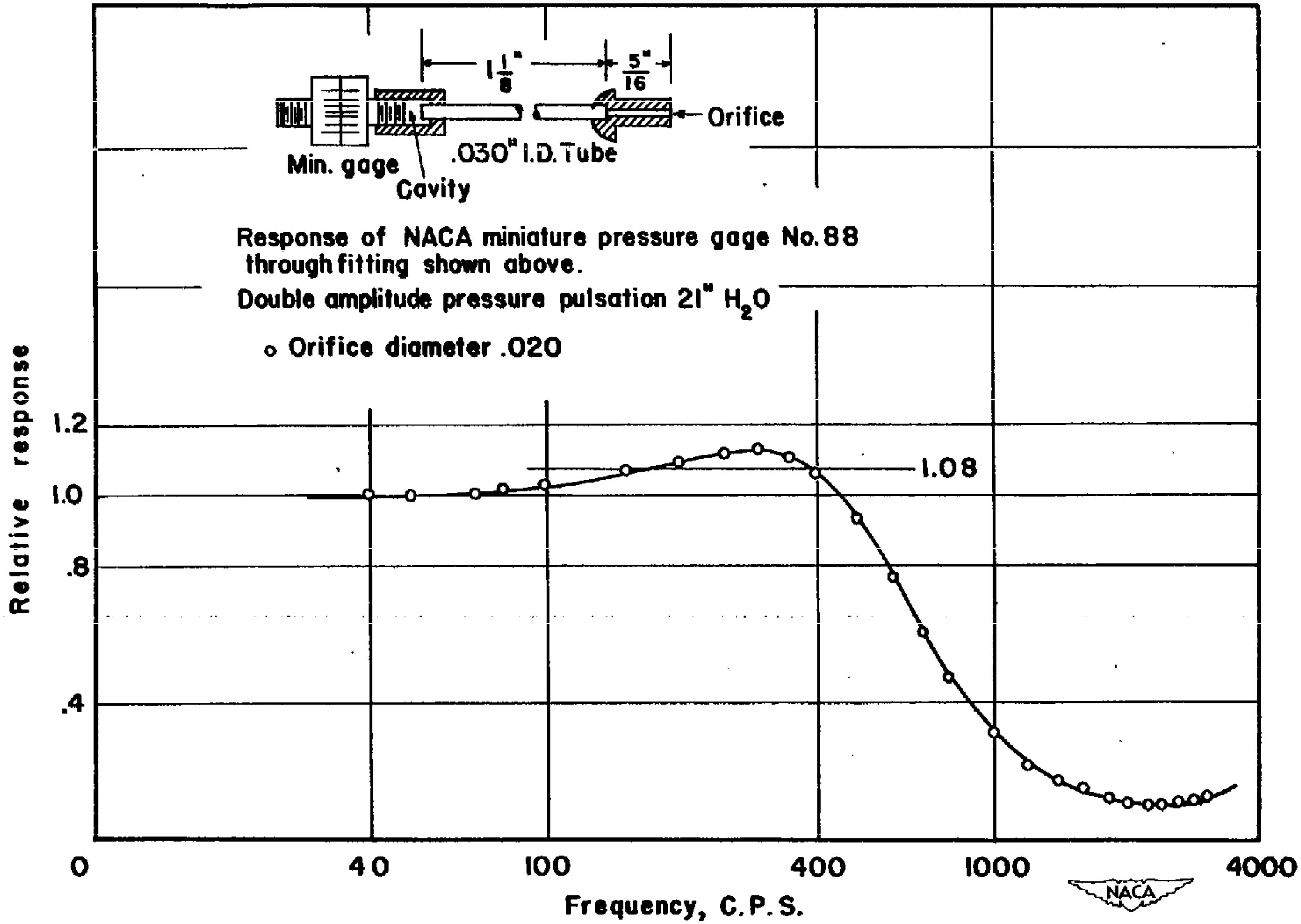

Figure 2.- Calibration of pulsating pressure measuring system.

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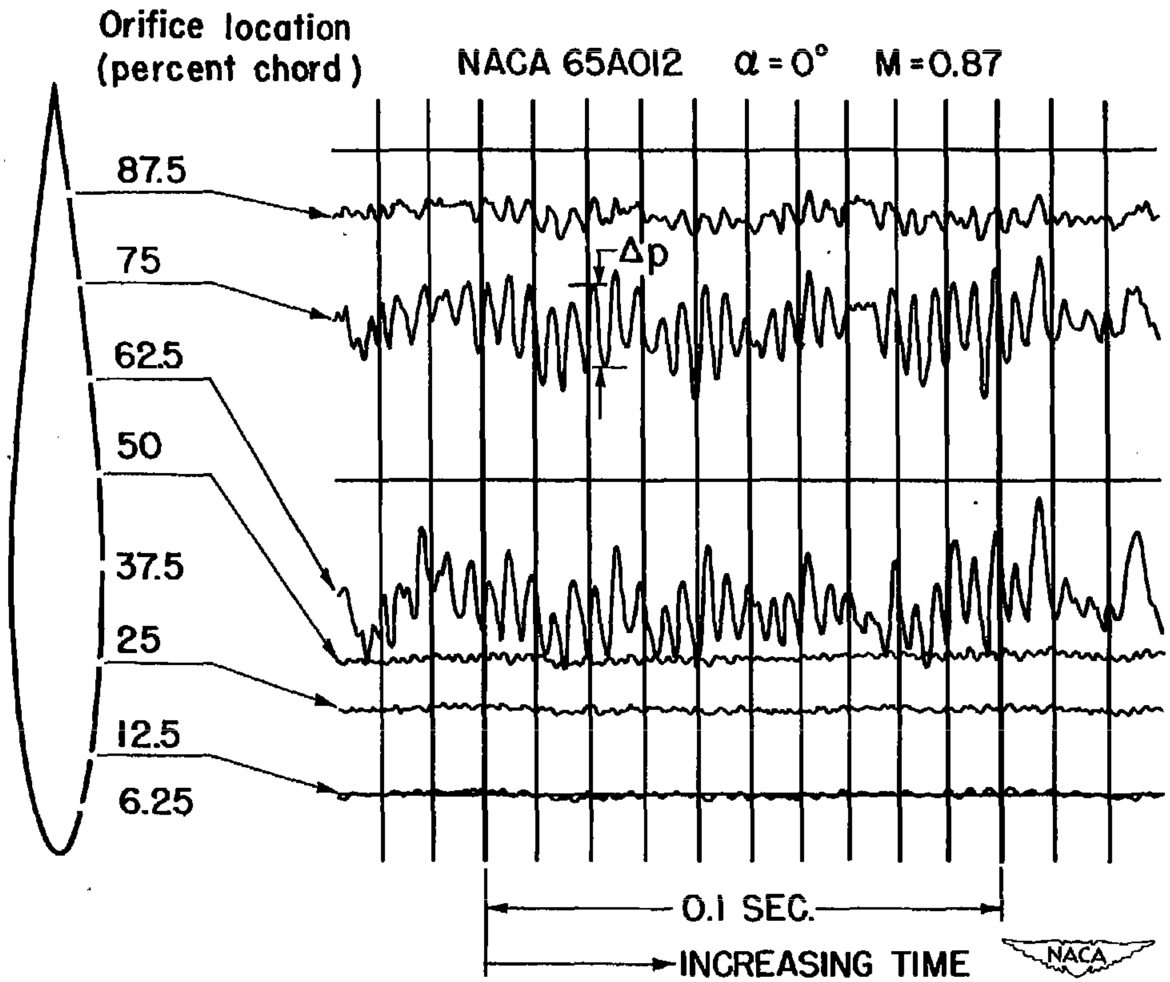
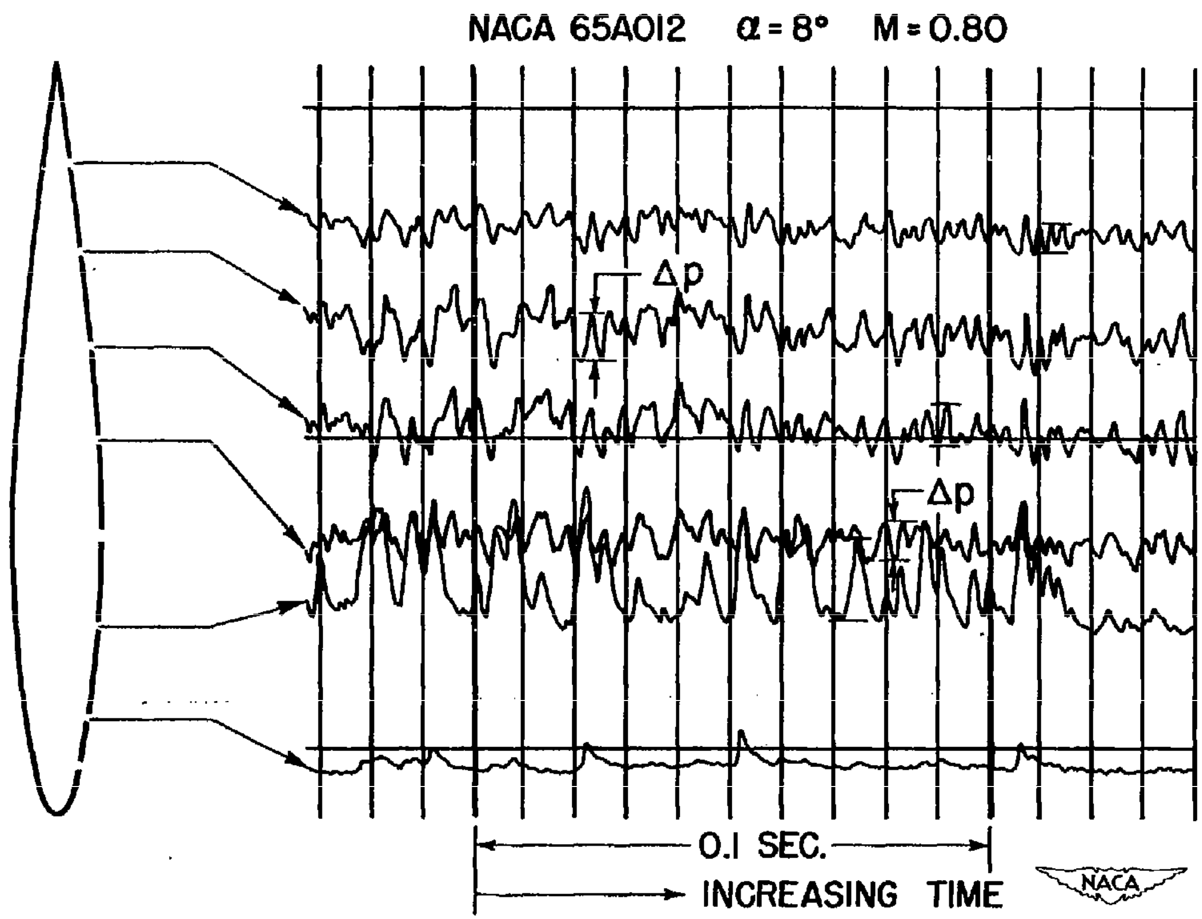


(a) Periodic-type pulsations at $\alpha = 0^\circ$ and $M = 0.87$.

Figure 3.- Airfoil profile and orifice locations with typical records of pulsating pressure measurements on NACA 65_1A012 airfoil.



(b) Random-type pulsations at $\alpha = 8^{\circ}$ and $M = 0.80$.

Figure 3.- Concluded.

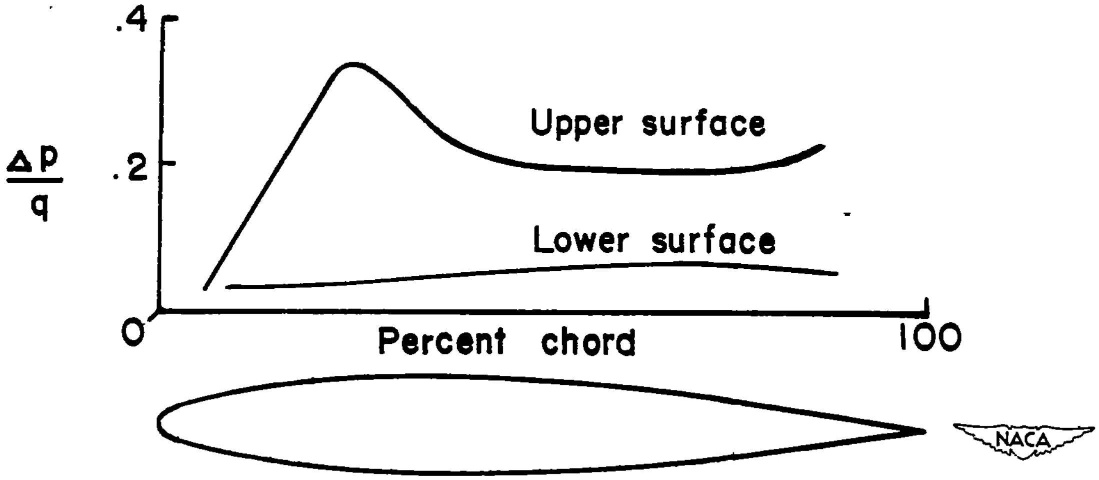
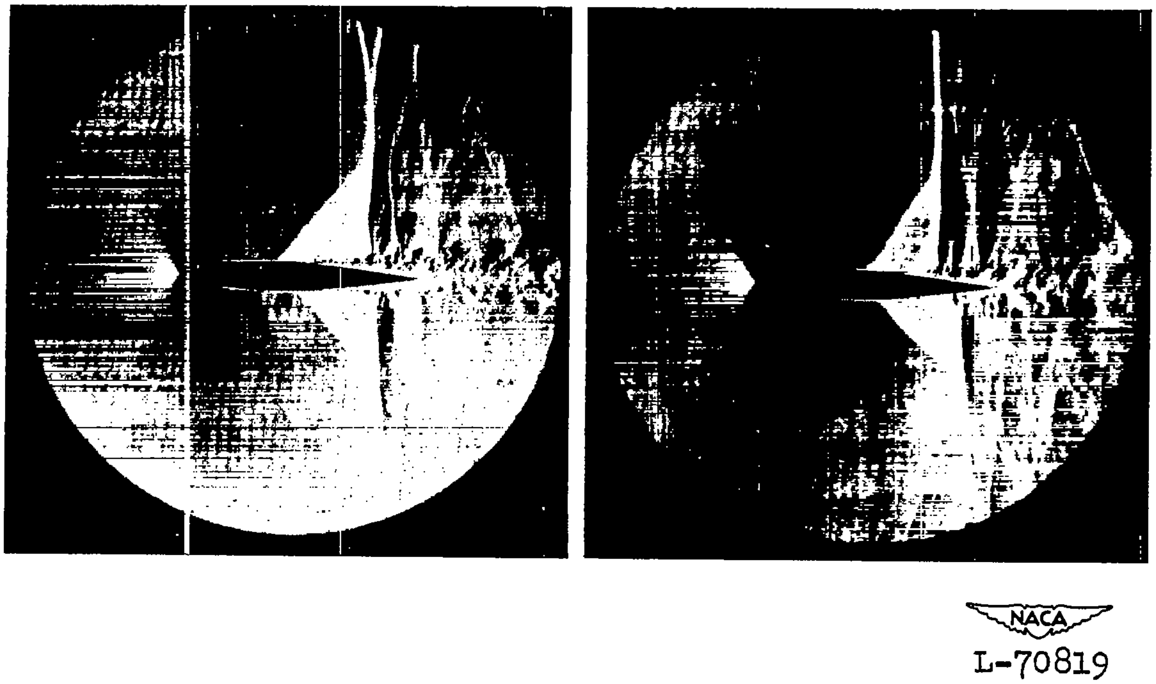


Figure 4.- Typical pressure pulsations on the airfoil surface. NACA 65_1A012 airfoil. M = 0.80; α = 8°.

(a) α = 0°; M=0.90; 5,000 frames per second.

(b) α = 6.4°; M=0.87; 5,000 frames per second.

Figure 5.- High-speed motion-picture sequences illustrating very rapid shock oscillation at low transonic Mach numbers on the NACA 65_1A012 airfoil.



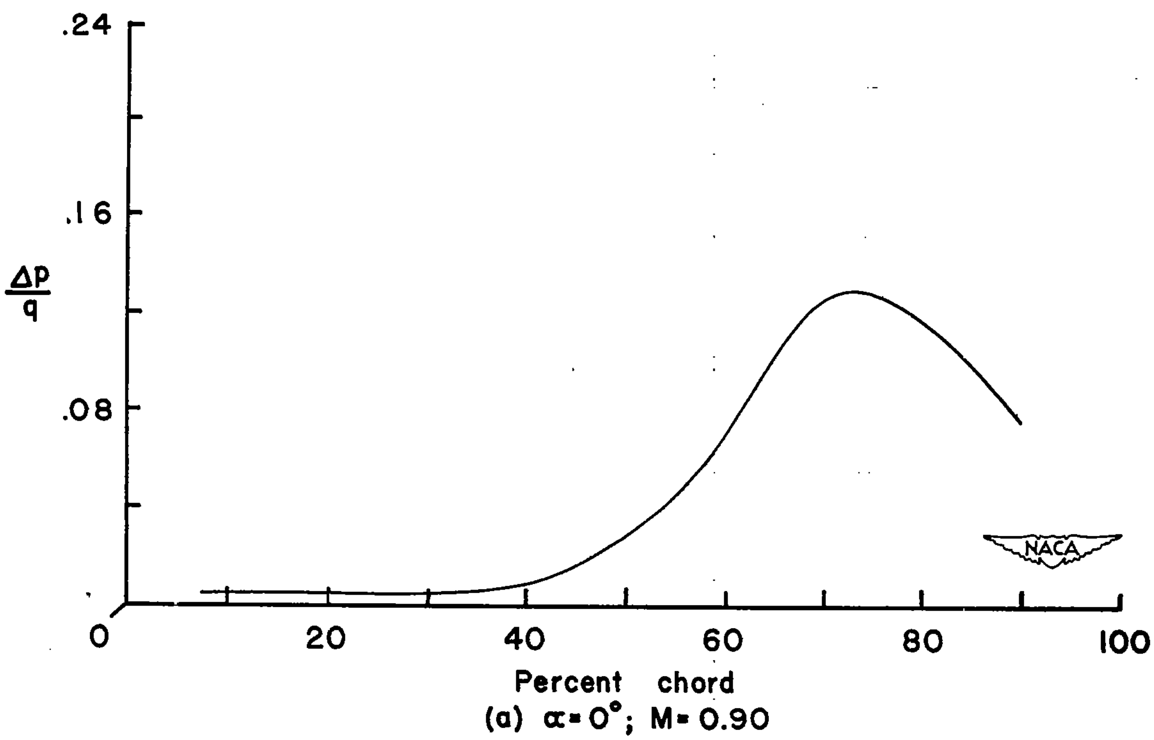
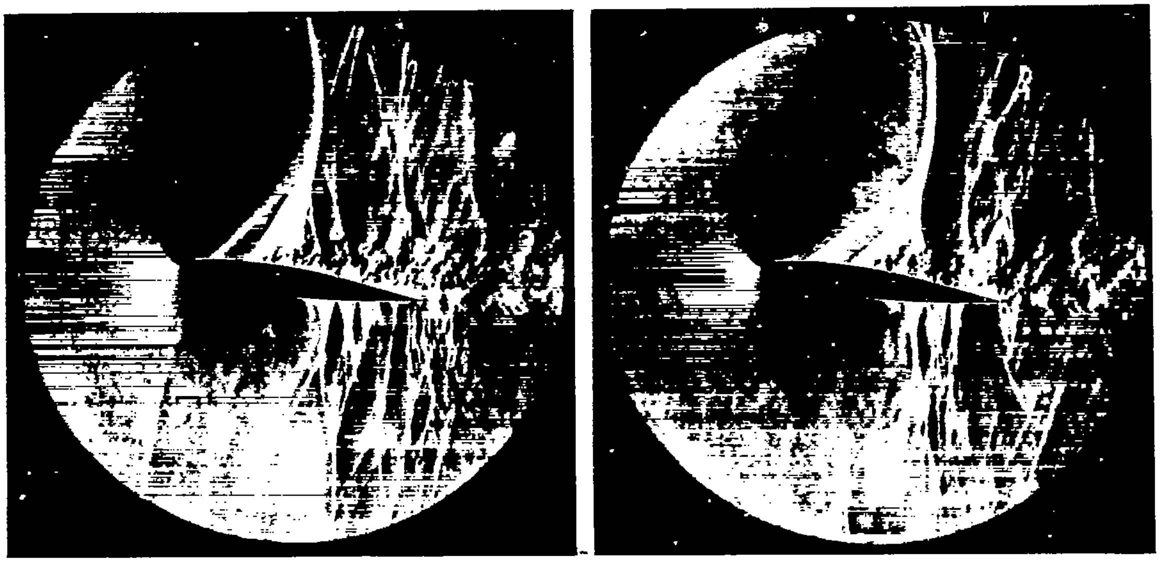


Figure 6.- Instantaneous schlieren photographs of the flow about the 4-inch-chord NACA 65_1A012 airfoil and the corresponding pressure pulsations on the airfoil surface.



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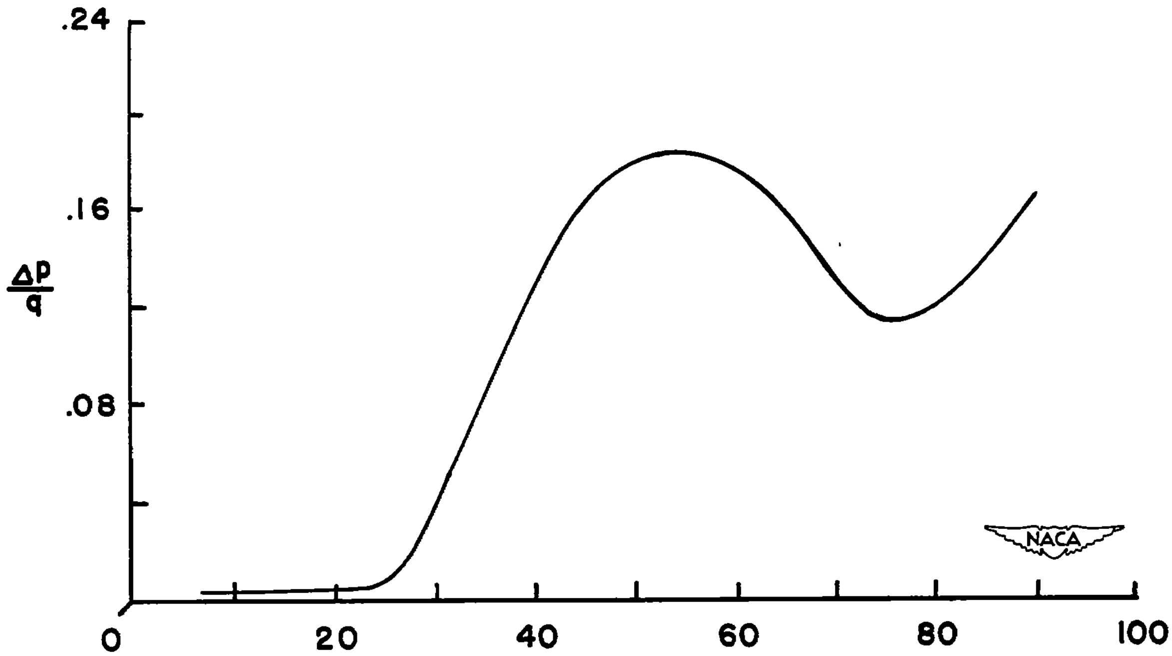
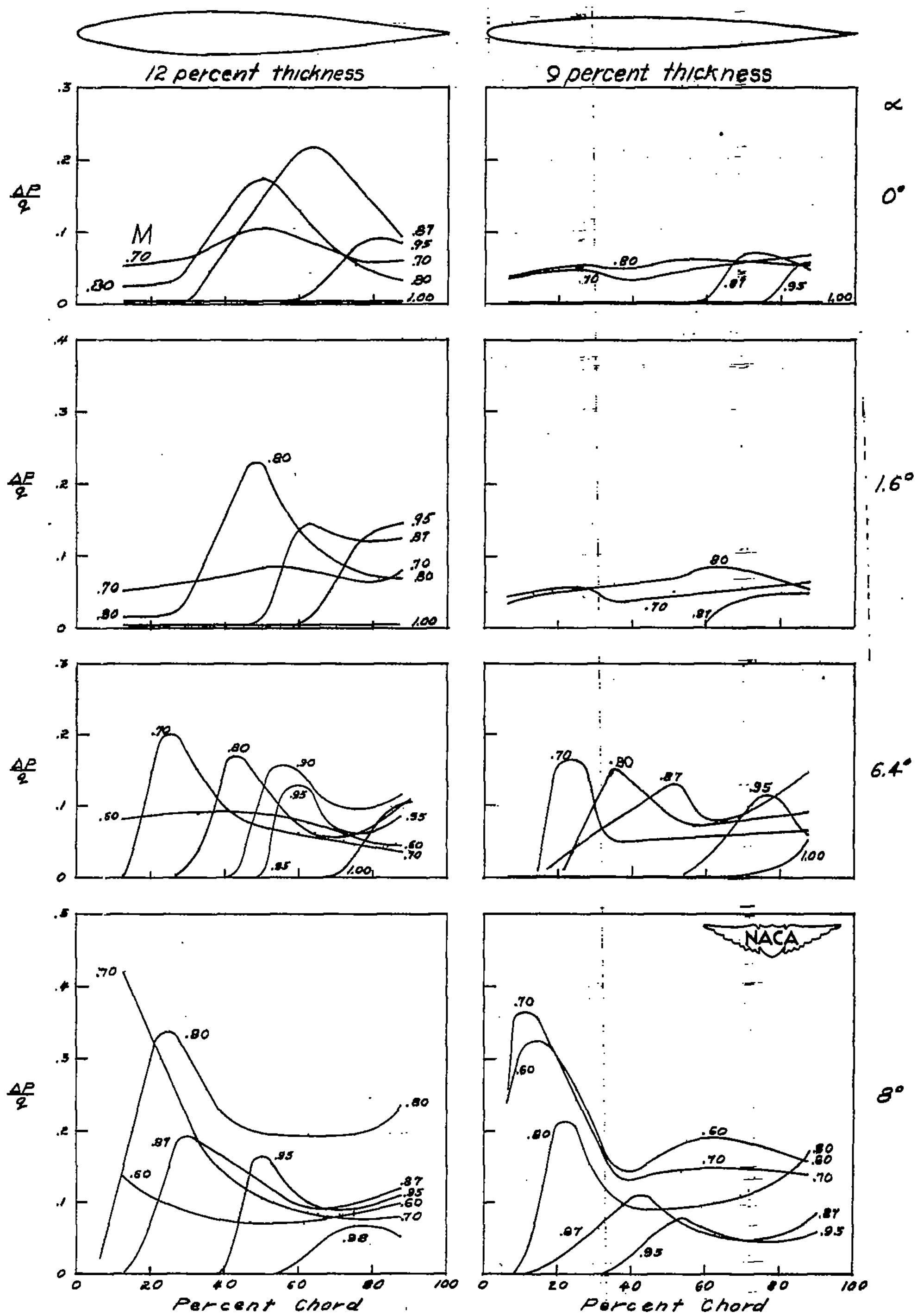


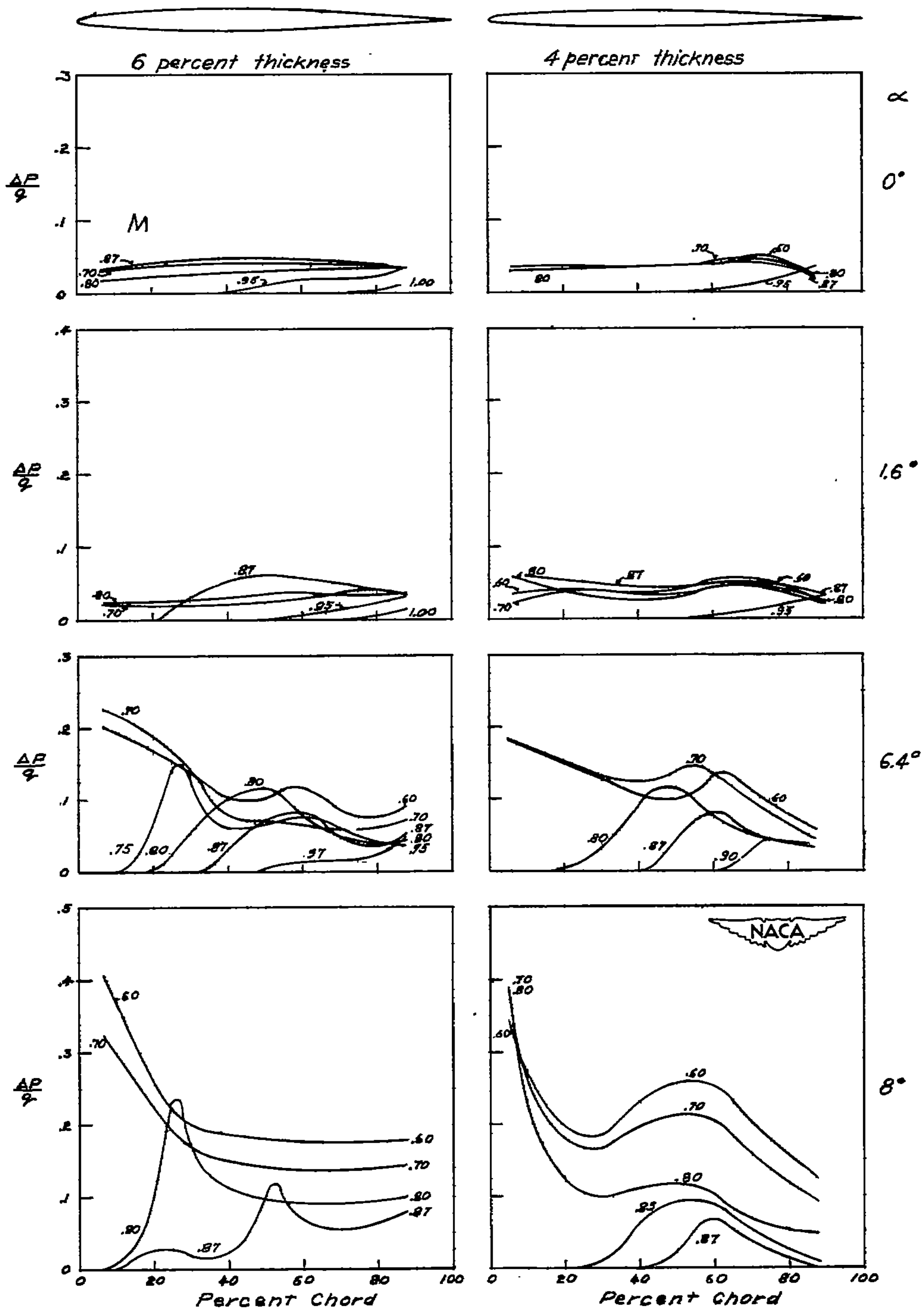
(b) $\alpha = 6.4°$; $M = 0.85$

Figure 6.- Concluded.



(a) NACA 65_1A012 airfoil. (b) NACA 65A009 airfoil.

Figure 7.- Chordwise pressure pulsations as affected by airfoil thickness, Mach number, and angle of attack.



(c) NACA 65A006 airfoil. (d) NACA 65A004 airfoil.

Figure 7.- Concluded.

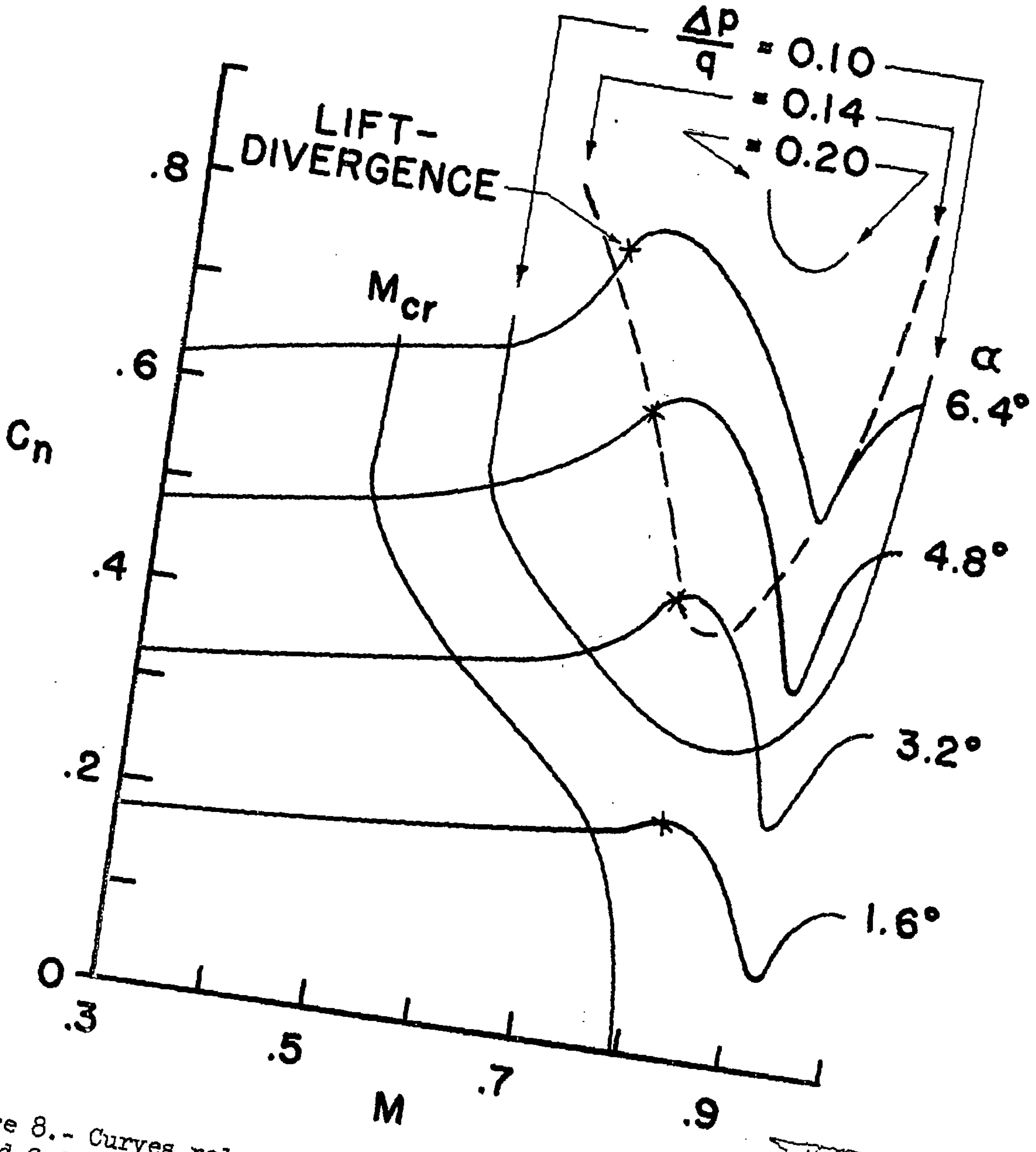


Figure 8.- Curves relating pressure pulsations $\Delta p/q$ of 0.10, 0.14, and 0.20 with normal-force changes on the NACA 65A009 airfoil.

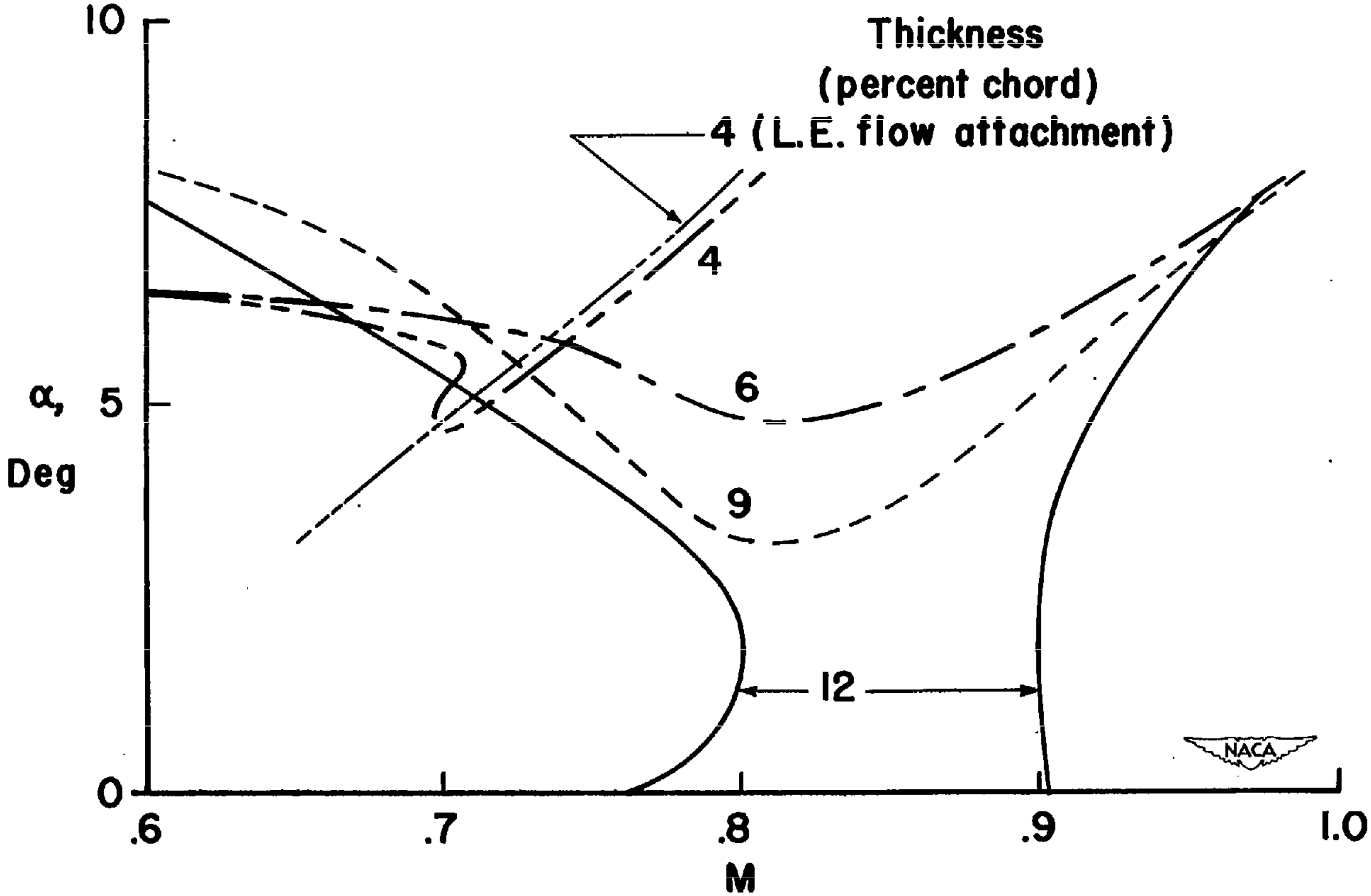


Figure 9.- Approximate flow fluctuation boundaries for $\frac{\Delta p}{q} = 0.14$ as affected by thickness.